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WiP: Developing a Contextual and Application-Based Instructional Approach for Mathematics Education in Engineering Programs

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Work in Progress (WiP):

Developing a Contextual and Application-Based Instructional Approach for Mathematics Education in Engineering Programs

Abstract:

In traditional post-secondary mathematics education for engineering students, a significant challenge is the disconnect between theoretical instruction and practical application. This gap often arises from teaching complex mathematical concepts in isolation, without contextualizing them within real-world engineering applications. To address this issue, we are developing and implementing a holistic, collaborative pedagogical approach that emphasizes contextualized, application-based teaching and learning, specifically tailored to mathematics-related classrooms in both engineering and mathematics disciplines. This paper shares our early insights and seeks feedback on our experimentation with teaching strategies such as problem-based learning in a second-year numerical methods course designed for engineering students.

With our primary goal of contextualized and application-based learning, we aim to create an enriched environment that equips students with the skills to effectively apply various numerical methods as engineering tools for solving complex real-world problems. Emphasizing practical applications, we have reviewed existing best practices, restructured the entire course, developed new materials and collaborative projects, and diversified assessments to better meet learner needs prior to implementation. In Fall 2024, we implemented our instructional approach, still in its development stage, in its first classroom setting. At the beginning of the term, we gathered pre-course reflections from students that guided our adaptations to teaching methods. Post-course feedback was used to evaluate the success of our implementation. Initial observations from this first iteration reveal both successes and challenges in promoting contextualized learning as educators. In addition to enhancing problem-solving skills and applying numerical methods to various real-world scenarios, we also emphasize the application of computer programming abilities, which are essential in engineering contexts.

Since our approach is still in the development phase and this is our first implementation iteration, we welcome constructive feedback from the audience to further refine and improve our approach. Through shared insights, we hope to enhance the effectiveness of our approach and ultimately improve outcomes in mathematics courses for engineering students. In future iterations, we aim to explore, and measure how context-based education support the overall well-being of learners throughout their educational journeys.

1. Introduction

Today's most pressing challenges, such as climate change, are often called complex or wicked problems because of their complexity and interconnectedness [1,2]. Solving such problems demands professionals who can effectively balance their specialized knowledge with a broader perspective. Particularly related to engineering profession, engineers must be able to apply the theories learned in the classroom to real-world solutions, addressing complexities through a systematic approach [3]. Context-based education in engineering programs is crucial in this regard, as it bridges the gap between theory and practice, enabling students to develop the essential skills needed to navigate this interplay [4,5].

Although there is widespread understanding of the importance of context-based education, the traditional 'chalk-and-talk' approach still dominates many post-secondary programs [6,7]. Particularly, mathematics in many programs is often taught as a set of abstract concepts, formulas, and algorithms, isolated from the real-world contexts in which these tools are applied. This teacher-centered, content-focused method, typically delivered through lectures, leads students to view mathematics as a collection of disconnected exercises rather than as an essential tool for solving complex real-world problems [7,8,9]. As a result, students often tend to memorize concepts and formulas to perform well on exams that assess theoretical knowledge, but they struggle to apply their mathematical learning to complex challenges.

To bridge this theoretical-practical gap in mathematics education, we need an approach that helps students truly grasp the material. This can be achieved by incorporating materials such as examples, in-class activities, and assessments that are relevant to students' discipline and connected to real-world problems [7]. When engineering students see how mathematics is used to solve engineering challenges, they are more likely to recognize the value of their learning. Chng et al., [10] emphasize that integrating activities, real-world data, and incorporating strategies like problem- and project-based learning (PBL) can significantly improve student engagement and understanding of mathematical concepts. “PBL begins when students are presented with an open-ended, ill-structured, real-world problem and work in teams to identify learning needs and develop viable solutions, with instructors serving as facilitators rather than primary sources of information” [11,12]. PBL fosters motivation to learn, encourages collaboration, problem-solving, and systemic thinking, while promoting creativity, communication, critical thinking, and self-directed learning, enabling students to acquire a broad range of knowledge, transferable skills, and competencies necessary to tackle complex, real-world problems [13,14]. While PBL also presents its own challenges, the creation of relevant and well-designed problems is essential for its successful implementation in the classroom [13,15].

This paper presents a detailed overview of experimenting with our pedagogical approach, which is still in the development stage, aimed at delivering contextualized and application-based mathematics education to engineering students. As we continue to develop this approach, we have selected the numerical methods course (SUSE 307: Numerical Methods and Computing Tools for Sustainable Systems Engineering) as the setting for its first implementation. SUSE 307, offered to second-year Sustainable Systems Engineering students at the University of Calgary, Canada, is an ideal starting point due to its focus on key mathematical techniques and computational tools essential for solving real-world engineering problems. It provides an opportunity to engage students at a critical stage of their education, where they can begin applying theoretical concepts to more complex, practical challenges. Furthermore, the relatively small class size enables more individualized attention, simplifies feedback collection, and allows for close monitoring of the new pedagogical approach's effectiveness, making it an ideal setting for testing and refining the approach before scaling it to larger cohorts or other courses.

To provide context for the course, numerical methods is a key course in engineering programs; however, the gap between theory and practical application is particularly noticeable. Numerical methods are effective in solving large systems of equations, handling nonlinearities, and managing complex geometries-challenges commonly found in engineering problems that are too complex to solve analytically-by providing the necessary tools to approximate solutions, enabling engineers to model, simulate, and optimize systems more accurately and efficiently. However, these methods are often taught from a theoretical perspective, leaving students with limited opportunities to apply them in practical scenarios such as system design, optimization, or simulations [16,17]. Furthermore, integrating programming into the curriculum is essential for preparing engineers to solve problems more efficiently by accelerating computations, automating tasks, and enabling the rapid analysis of large datasets to generate insights and predictions, ultimately improving real-world problem-solving and minimizing errors [16].

The following sections of the paper will outline our process in developing and implementing the instructional approach, provide reflections from both students and instructors, highlight success stories and challenges, and discuss future directions.

2. Outline of Our Process

Our team is composed of three members from the Faculty of Engineering and two from the Department of Mathematics and Statistics. Through this collaboration, we aim to refine and strengthen our approach to ensure it is as cohesive and effective as possible, integrating the strengths of both fields to enhance student learning and bridge the theoretical-practical gap. Our process in developing such instructional approach involved several key steps:

- Conducting a literature review
- Restructuring the courses and lectures incorporating context-based activities
- Developing project- and problem-based tutorials and assignments
- Implementing and integrating changes into classroom practices
- Collecting pre-course students' feedback through anonymous survey
- Collecting post-course students' feedback through anonymous survey

2.1 Research Question

Considering the theoretical-practical gap in mathematics education, the overarching research question we aim to address through this collaborative project is: "How can we integrate innovative, context-based teaching methods and strategies to enhance student learning of mathematical concepts and improve their ability to apply this knowledge in various situations, particularly in complex, real-world problem-solving?". With this overarching research question in mind, our goal was to redesign a numerical methods course (SUSE 307) that would enable engineering students to apply the tools learned in the classroom to solve real-world problems.

2.2 Key Steps of the Process

We began by conducting a literature review on existing context-based pedagogies and assessing their relevance to our educational setting. Next, we examined the current curriculum of SUSE 307 to identify theoretical concepts that students often struggle to apply in practice. After identifying key concepts and reviewing relevant insights from the literature, we shifted our focus to restructuring the course by adding new modules, lessons, and assignments that systematically integrated real-world applications and examples. In parallel, we created comprehensive projects and problems focused on sustainable systems, along with both individual and team-based problem-solving assignments, to foster collaboration and deepen students' learning experiences.

We have structured SUSE 307 into two types of learning environments: classes based on lectures (3 hours weekly) and tutorials (2 hours weekly) with more hands-on activities. The lectures began by emphasizing the practical applications of the concepts, helping students understand why and where to apply the knowledge before delving into the theoretical aspects and solving equations. The theory was taught in class with simpler hand calculations, emphasizing numerous examples and real-world applications. The tutorials were aligned with the lectures, providing students with the opportunity to apply numerical tools and programming skills in problem- and project-based assignments, with tutorials offering additional support.

In Fall 2024, we implemented this approach in a classroom of 16 second-year students. At the start of the course in September 2024, a pre-course feedback survey was conducted to evaluate students' prior knowledge, preferences, and attitudes toward mathematics education in general. Upon completion of the course and implementing these changes, in December 2024, post-course feedback survey was collected to gather students' learning experiences with the restructured course and context-based approach, comparing it to their previous mathematics courses.

2.3 Components of Course Assessments

SUSE 307 included a variety of assignments and assessments as shown in Table 1. The problem-based assignments were smaller in scope and individual submissions. The project-based assignments were larger in scope, required more critical thinking and allowed group submissions. The problem-based assignments required developing a single solution for a smaller problem, whereas the project-based assignments focused on creating multiple viable solutions for more complex issues and evaluating the best option under specific conditions. The tasks required the use of numerical methods and programming.

The two midterm exams, which were open note, aimed to assess students' ability to apply theoretical knowledge to various engineering problem-solving scenarios. The concept checks were designed to encourage independent problem-solving. In addition, students were asked to complete three reflective assignments to evaluate their learning, assess their progress, and identify areas for improvement. The first reflection and the midterm reflection were specifically aimed at helping students apply their insights to the remainder of the semester.

Table 1: Course Assignments and Assessments

Assignment Description	% Grade
3 problem-based assignments, individual	15
3 project-based assignments, group of two	30
2 midterm exams, open notes, non-cumulative	40
4 concept checks, individual	10
3 reflective assignments	5
Total	100

2.4 Structure of Context-Based Tutorial Sessions and Assignments

We designed the tutorial sessions to focus on problem solving, applications of numerical methods and programming, while also supporting students in working through problem- and project-based assignments. In the planning and preparation phase, we determined the scope of the tutorial, ensuring it focused on problems that could be expanded through programming to address larger challenges beyond manual solutions. We then compiled a list of real-life problems that could be modeled and solved using the numerical methods introduced in the tutorial, refining it to include problems that were either impossible or impractical to solve analytically, with a focus on sustainability to align with students' interests and enhance engagement.

During each tutorial session, we followed a structured approach to lay the foundation and develop solutions. The sessions began with a Gapminder [18] quiz to capture students' attention right away, followed by the presentation of a real-world sustainability problem to emphasize its relevance. After introducing a mathematical model and discussing its analytical limitations, we presented a numerical method, revisited the class theory, and outlined the steps for implementing the solution. Students were encouraged to actively participate, suggest test scenarios for smaller components, identify errors, and deepen their understanding of the algorithm. Finally, we visualized the results and reviewed the problem, method, and solution. The steps are summarized in Figure 1. The deliverables for problem- and project-based assignments included submitting a project report, which should contain an introduction and problem definition, the methodology, results with supporting graphs, a discussion and analysis of the observed trends, responses to several critical thinking questions, and conclusions.

In total, we conducted ten tutorial sessions. Table 2 summarizes the context of the theoretical concepts and real-world problems used in the tutorials and their assignments. Furthermore, we also highlighted how each problem was linked to one or more of the United Nations Sustainable Development Goals (SDGs), emphasizing the relevance of numerical methods in addressing key sustainability challenges [19]. This process helped students understand the broader impact of their work and encouraged critical thinking about how mathematical tools can contribute to solving global issues like climate change, resource management, and social equality.

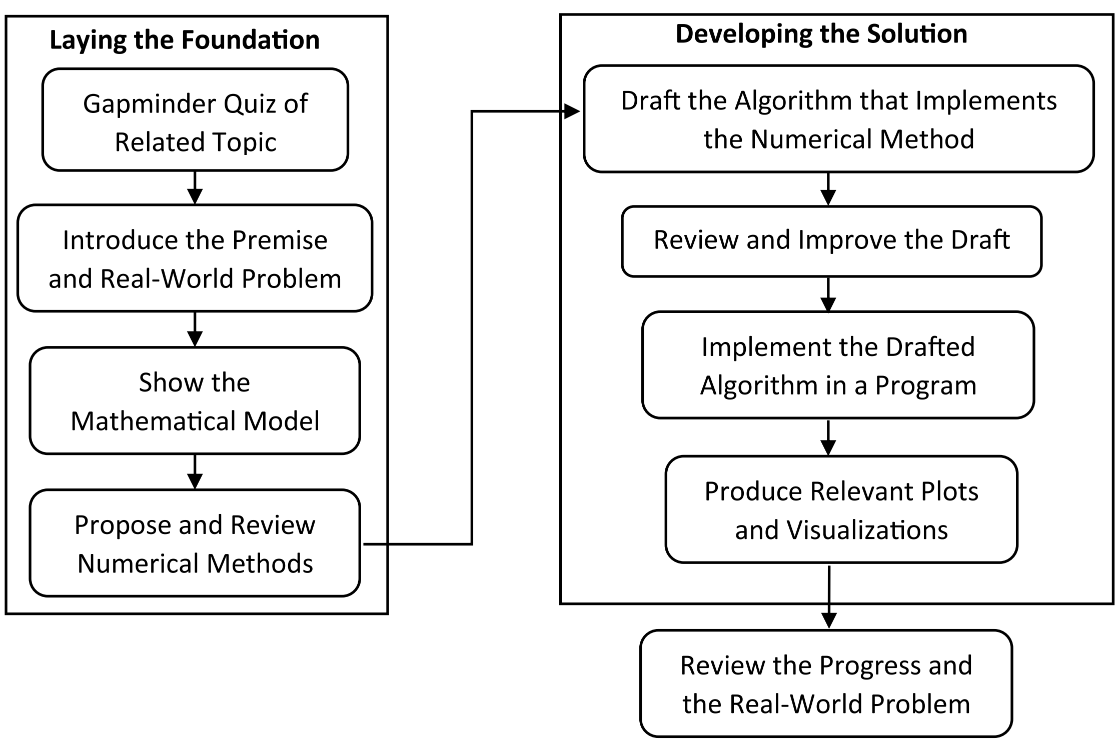


Figure 1: Tutorial Delivery Structure

Table 2: Context of the Assignment Problems

Tutorial Number	Theoretical Subject	Real-Life Problem	Assignment	Problem Description
1	Root finding (Bisection and, Newton-Raphson methods)	Model the concentration of a pollutant in a body of water	Problem-based (Individual)	Find the root of a pollutant concentration function using bisection method
2	System of linear equations (Gaussian Elimination method)	Interconnected rooms with air pollution and wind currents	Practice programming - no assignment	Determine the concentration of air pollutant in each room solving resultant set of equations
3	Linear regression	Real-world data for CO_2 emissions from Gapminder	Problem-based (Individual)	Numerically find a Lagrange polynomial that fits Gapminder data
4	Interpolation (Lagrange Polynomial)			
5	Numerical optimization (Optimization with constraints)	Warehouse-to-store distance to minimize transport emissions	Project-based (Team of two)	Optimize cost and CO_2 emissions of a diet with sufficient nutrients for an adult
6	Numerical optimization	Diet optimization to minimize cost with nutrient requirements		
7	Numerical optimization	Power grid optimization to minimize cost and emissions	Project-based (Team of two)	Optimize cost of an offshore wind power farm
8	Ordinary differential equations (Euler's method)	Fish population and harvest model to evaluate sustainability	Project-based (Team of two)	Model and solve Lotka-Volterra equations for a prey-predator system
9	Systems of ordinary differential equations (Runge-Kutta method)	Evolution of contagious diseases (SIR model)		
10	Numerical integration (Trapezoidal method)	Solar power produced by a panel at a certain time of the day	Problem-based (Individual)	Calculate the integral of solar panel power using trapezoidal and Simpson's rule

3. Reflections from Students

To evaluate the effectiveness of our context- and application-based teaching approach, we conducted pre- and post-course feedback surveys. Participation was voluntary and anonymous. The pre-course survey achieved a 62.5% response rate, while the post-course survey had a 75% response rate. The main goal of the surveys is to compare students' prior experience with numerical courses to their experience in SUSE 307.

3.1 Pre-Course Feedback

The pre-course feedback survey was designed to gather specific information about students' experiences with numerical courses, particularly how traditional teaching methods influenced their success and whether they contributed to enhanced learning. It aimed to establish a baseline for understanding students' perceptions of previous mathematics courses, enabling a comparison with the context-based teaching methods used in this course. The survey included questions about students' anxieties and challenges in numerical courses, their ability to grasp both theoretical and practical concepts, and the techniques they had used to understand complex mathematical theories. Additionally, it explored the strategies students believed would be beneficial for instructors to incorporate in this course to enhance learning.

Students shared a variety of anxieties and challenges related to their previous experience with numerical courses. Many struggled with time constraints and self-directed learning, especially when there was limited opportunity for in-depth practice, with some attributing their difficulties to the "sheer volume of course material rather than the concepts themselves". Several students emphasized the need for "well-organized, example-rich materials and the importance of connecting mathematical concepts to real-world applications rather than focusing solely on abstract theory." Many felt that the "focus on rote memorization in these courses limited their ability to develop a deeper understanding of the material." A recurring issue was the "format of long, calculation-heavy exam questions, particularly multiple-choice questions for complex calculations", which many students felt did not truly reflect their understanding and led to discouragement.

Students reported finding it "easier to understand mathematical concepts when connected to real-world applications." Many expressed a preference for seeing how math is applied in real-life situations, as this not only helped them engage more deeply with the material but also greatly increased their interest in the topics. One student highlighted the importance of visualizing math in a way that was more accessible, pointing out the challenge of traditional mathematical notation for those who think more visually.

Students employed various strategies to master mathematical concepts, with many emphasizing the importance of consistent practice and working through practice problems. To make the material more tangible and relevant, some students related concepts to real-world issues or personal experiences. Others found success in techniques like solving examples backwards or identifying patterns across similar problems to deepen their understanding. Many students also benefited from working with classmates, receiving one-on-one tutoring, or attending office hours, while some preferred smaller classes where they felt more comfortable asking questions. Additionally, creating cheat sheets to organize key formulas helped some students manage the material and feel less overwhelmed.

Students commonly suggested that mathematics education could be improved by incorporating more hands-on practice problems. They emphasized a preference for teaching styles where instructors work through problems step-by-step, taking the time to slow down and provide thorough explanations, rather than simply reading from slides. Students also wanted instructors to avoid assuming prior knowledge and to ensure that they clearly explain concepts from the ground up. There was a strong desire for more collaborative problem-solving in class, with plenty of opportunities for students to ask questions and work together with peers. Other recommendations included improving the pacing of both lectures and tutorials to prevent rushing through material, offering lecture notes in advance for review, and creating a comfortable environment for students to ask questions without feeling self-conscious. Additionally, one student suggested using more engaging and visual teaching methods, such as highlighters, 3D models, or physical demonstrations, to make the material more accessible and less abstract.

In response to students' pre-course survey feedback, while emphasizing context- and application-based teaching, alongside ample step-by-step problem-solving practice, we also aligned lectures with tutorials, adjusted the pacing of lessons, provided clear notes and expectations, and designed assessments to effectively measure students' knowledge and understanding.

3.2 Post-Course Feedback

After the semester concluded in the second week of December 2024, we conducted the post-course feedback survey. Post-course feedback survey included five open-ended questions designed to understand their personal learning journey throughout the course, as well as five multiple-choice questions for comparison with future iterations of the course. The open-ended questions focused on several areas such as: what aspects of the course they appreciated most, the challenges they encountered, their suggestions for overcoming those challenges, whether the context-based learning approach helped them retain the material more effectively than traditional methods, and why, and if this approach impacted their study habits or routine in any way.

Students expressed strong appreciation for structure of the course and teaching style, particularly the focus on step-by-step explanations of methods followed by immediate practice examples, which made concepts easier to understand and apply. Many students found the combination of theory and practical application highly effective, especially with the integration of tutorial sessions that helped solidify their understanding of numerical methods. One student noted, "both the theory and examples were covered, making it easier to understand and solve practice problems. The tutorials were interesting and helped solidify my understanding of numerical methods." The open-book assessments were praised for reducing stress and encouraging a focus on comprehension rather than memorization. Students also appreciated the clear content delivery, the opportunity to compare different methods, and the hands-on coding experience that demonstrated how to apply mathematical concepts in real-world scenarios. Overall, students felt confident in their ability to apply what they had learned and valued the practical nature of the course. As one student noted, “I really enjoyed the content of this class. I think the way that the content was taught was very straightforward and doing lots of examples and applications in class helped me feel more confident about practicing on my own.”

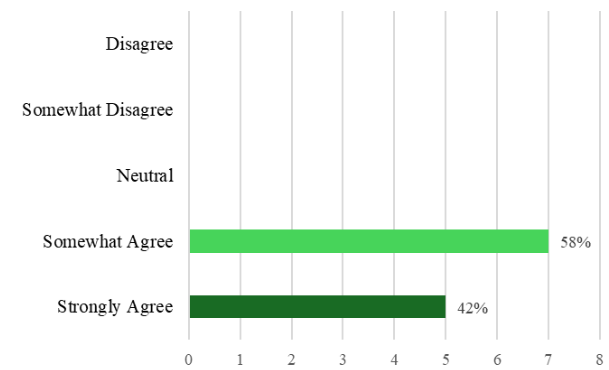
The most common challenge students encountered throughout the course was the programming aspect, particularly for those less confident in Python. As one student noted, "I found the programming to be quite challenging as it is not an area that I am confident in." Many students found the “programming requirements more time-consuming than expected, especially given that the course was not explicitly designed to be coding-intensive.” Additionally, students found the assignments to be overwhelming, particularly when they combined theory, application, and programming in a single project. To address these challenges, students recommended simplifying some of the coding tasks and focusing tutorials and assignments more on practical applications rather than deep coding.

Students appreciated seeing how the methods learned in class applied to real-life scenarios, which helped them make connections and better understand the purpose of the material, with one student noting, "seeing examples was great, having it in the context of sustainability made it worth while learning," and another saying, " using the methods taught in class to solve real world situations helped solidify those concepts as now I have context for them." Overall, while students felt the course did a good job with context-based learning, they suggested that incorporating more detailed real-world applications and industry-related scenarios would enhance their understanding and retention of numerical methods. More emphasis on sustainability in class examples and including visual aids for qualitative explanations were also mentioned as potential improvements.

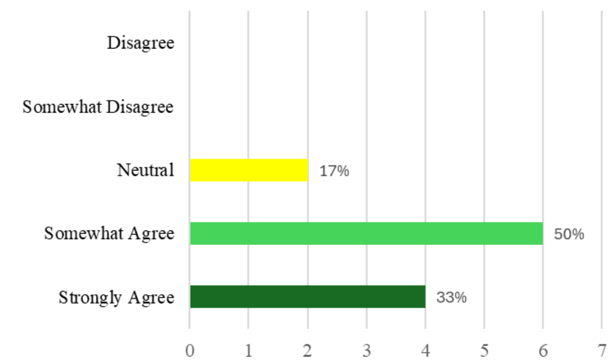
Many students found that the context-based approach significantly improved their understanding of the content, increased their efficiency, and helped them manage their study time more effectively. One student mentioned, "The context-based approach combined with in-class examples meant I was less confused when I went home. I didn’t need to re-learn the content and could just start solving more problems. It saved me a lot of time and made me less frustrated,". While the context-based approach didn’t drastically change everyone's study habits, it made the material easier to understand and apply, reducing the need for extensive re-learning.

Figure 2 displays the responses we received for the five multiple-choice questions in the post-course feedback survey. The x-axis represents the number of students' responses. While we currently do not have a comparison, we plan to use these trends and responses for comparison with future iterations of the course. In summary, students expressed that the use of applications and real-world examples significantly improved their understanding of numerical methods. They also felt that context-based learning enhanced their exam performance. As a result, they are confident in their ability to apply theoretical knowledge to solve complex problems.

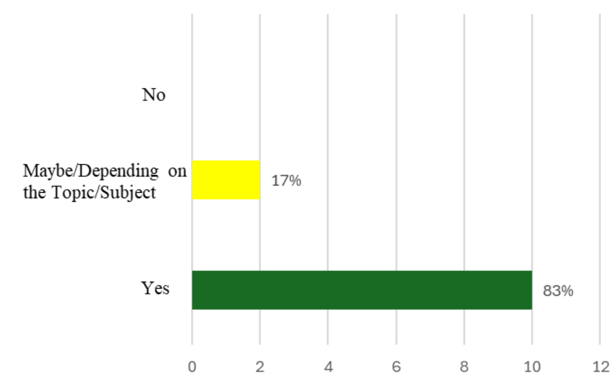
Q#6 I found that applications, real-world examples, and problem-solving in SUSE 307 helped understand numerical methods more clearly.



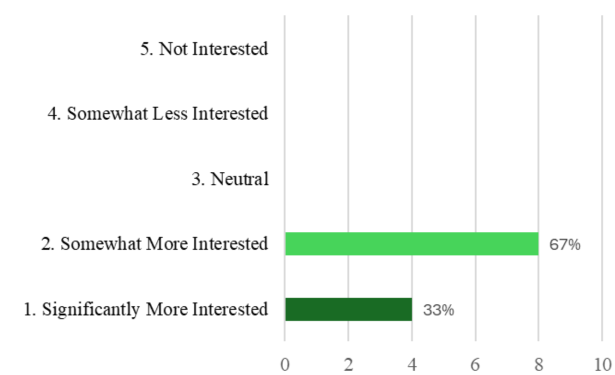
Q#7 Context-based learning has effectively prepared me for solving questions in my exams and assignments in the course compared to other math concepts.



Q#8 Based on your experience, would you like future classes to incorporate context-based learning?



Q#9 On a scale from 1 to 5, how much more interested did you become in learning numerical methods after seeing them applied to real-world contexts?



Q#10 How confident are you in applying numerical methods to real-world problems compared to applying mathematic concepts learned in other math courses?

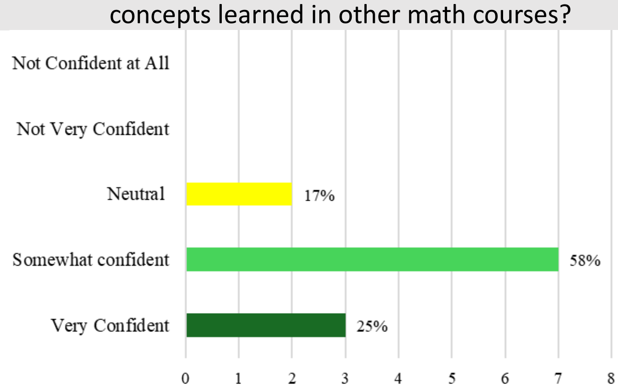


Figure 2: Post-Course Feedback Survey Response to Multiple Choice Questions

4. Reflections from Instructors

Once the post-course feedback survey was completed, our project team gathered to reflect on our first iteration and identify areas for improvement in future iterations. We also discussed how to apply these insights to a larger classroom setting in one of the Statistics courses offered by the Department of Mathematics and Statistics in Winter 2025.

Overall, instructors felt that SUSE 307 was better structured than in previous year, and it was well-received by students. The process of preparing and restructuring the course including creating appropriate problems and projects was challenging and time-consuming, but the support from research assistants who had previously taken the course proved invaluable during this phase. Finding the right balance between the preparation time and effort required when restructuring course content is always a challenge from an instructor's perspective. Moving forward, we recognize the need for more sustainability-related examples and a broader variety of industry-relevant projects and case studies to enrich the course content. This will allow us to continuously improve and ensure the material remains practical and engaging.

As students take a programming course in their first year, we anticipated that they would come in with fundamental coding knowledge, allowing us to build on that foundation throughout the course. However, when many students identified programming as their biggest challenge, we identified the need for improvement in how we incorporate coding in the course. To address this, we plan to introduce a 'Programming Overview Module' for self-study, which could be completed either prior to or alongside the course. Additionally, clearer communication about coding expectations from the start will help students better prepare for the technical aspects of the course.

In future iterations, we are considering shifting more weight toward the concept checks and problem- and project-based assignments [20], a change that was also suggested by several students, as they felt these assessments better reflected their understanding of the material. We are also exploring the use of non-traditional assessments moving forward, gradually shifting away from midterm exams. This transition will involve slowly decreasing the weight of the midterm exams in favor of alternative assessment methods, yet to be explored, particularly tailored to our course. We found that only a small percentage of students attempted to use AI tools for report writing in their project-based assignments. This has been an ongoing challenge, particularly with non-traditional assessments. However, further research is needed to gain a better understanding of the ethical use of such tools in student assignments and assessments, including ethical use of AI-based tools as programming assistant.

Another key observation was that student engagement with the course material, through attending classes, participating in tutorials, and completing assignments on time, was closely linked to their final grades. The context-based approach, practiced in class through step-by-step problem-solving with dedicated work time, is further reinforced through tutorials and assignments. When students actively engage with these activities, it contributes to their success and helps them achieve good grades.

5. Conclusion and Future Directions

This paper presents a systematic approach to teaching numerical methods in engineering, focusing on bridging the gap between theoretical knowledge and real-world application through a context-based, application-driven instructional approach. By integrating these methods into a Numerical Methods course, we aimed to better prepare students for the complex challenges they will face as engineers.

Based on student feedback, they believed the context-based approach effectively helped them connect mathematical theory to real-world applications, thereby enhancing their problem-solving skills. They particularly valued the application of mathematical concepts to sustainability challenges, which made the material more relevant and engaging. While we believe the approach was successful, feedback also revealed challenges, particularly with the programming component. This highlights areas for further refinement, such as improving coding instruction through a dedicated self-study module and exploring alternative assessment methods to better reflect students' problem-solving abilities.

However, the process of refining this course is ongoing, and the initial implementation is just the first iteration of a broader, long-term strategy. Looking ahead, we plan to expand the use of context-based teaching methods to other courses, with a stronger emphasis on real-world case studies and industry-relevant scenarios. We also aim to refine the course structure by balancing preparation time with content delivery and improving support for larger classrooms. By continuously incorporating student feedback and evolving teaching practices, we hope to create a more engaging, and effective learning experience for future cohorts, better preparing them to address the complex challenges.

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*** Some sentences in this paper were refined with the help of AI-generated tools to enhance quality. The ideas themselves were original and collaboratively developed by the co-authors.